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Comment on "Magnetic Geometry and Physics of Advanced Divertors: The X-Divertor and the Snowflake" [Phys. Plasmas, 20, 102507 (2013)]

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Comment on "Magnetic geometry and physics of advanced divertors: The X-divertor and the snowflake" [Phys. Plasmas, 20, 102507 (2013)]

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Abstract

In the recently published paper "Magnetic geometry and physics of advanced divertors: The X-divertor and the snowflake" [Phys. Plasmas, 20, 102507 (2013)], the authors raise interesting and important issues concerning the divertor physics and design. However, the paper contains significant conceptual errors: a) The conceptual framework used in it for the evaluation of the divertor "quality" essentially reduces this evaluation to the assessment of the magnetic field structure in the outer SOL. This framework is incorrect because the processes that encompass the pedestal, the private flux region and *all* of the divertor legs (four, in the case of a snowflake) are an inseparable part of the divertor operation. b) The concept of the divertor index focuses on only one feature of the magnetic field structure and can be quite misleading when applied to guide divertor design. c) The suggestion to rename the divertor configurations experimentally realized on NSTX and DIII-D from snowflakes to X-divertors is not justified: it is not based on the comparison of these configurations with the prototypical X-divertor and it ignores the fact that the NSTX and DIII-D poloidal magnetic field geometries fit very well into the snowflake "two-null" prescription.

The recently published Ref. 1 is concerned with divertors that are based on manipulation of the poloidal magnetic field structure, in particular, the X-divertor [2-4] and the snowflake (SF) divertor [5-7].

In the Introduction, the authors state that their approach is "based on an investigation and examination of the detailed structure of the magnetic field of advanced divertors in only the physically relevant region for power exhaust—the Scrape-Off Layer (SOL) terminating on the divertor plates." From the subsequent discussion and figures it becomes clear that the authors are actually considering only the zone of the common flux region of one branch of the SOL (the outer one, if we use a commonly accepted convention that the geometrical axis is situated to the left of the null-point in the pictures of the poloidal cross-section, see, e.g., Figs. 2-6. of Ref.1).

In reality, the power exhaust and the divertor performance are affected by a variety of processes *not limited to the outer SOL* that can play a critically important role for the divertor performance. These processes include (but are not limited to):

- processes in the so-called core pedestal region just inside the main separatrix (affected by the magnetic shear, resonant magnetic perturbations, velocity shear, prompt ion losses) that influence both the SOL structure between intermittent edge localized modes (ELMs, Ref. 8) and "germination" of ELMs.
- ELMs and their effect on the heat load (in particular, significant asymmetries in the energy deposition between outer and inner targets, with more energy dumped into the inner target [9]).
- Energy and particle flux redistribution between the multiple (more than two) divertor legs and associated separatrix strike points as in the snowflake divertor.

These processes (see a brief review in Ref. 10) are an integral part of the physics of the snowflake divertor, with its large area of a weak poloidal magnetic field near the second-order null (or two nearby first-order nulls), but they are of importance for the standard (single X-point) divertors as well. So, attempting to relate the divertor performance solely to the field structure in the common flux region of a single leg (Figs. 2-6, and further figures in Ref. 1) is very misleading.

Our second concern is related to the discussion of the relation between the SF and X-divertor as given in Ref. 1. Here we present our view on this relation.

For practical applications, it is desirable that the coils generating the divertor magnetic field be situated far away from the divertor. This constraint has been incorporated in the analyses of the snowflake divertor from its inception, Refs. 5,6. Then, the flux function determining the magnetic field is a smooth function of spatial coordinates in the poloidal plane (say, x,y) centered in the area of interest. This function can then be expanded in a Taylor series over x,y. The corresponding expansions, using up to the third-order terms, have proven to be quite efficient and accurate [6,7]. Possible configurations based on these expansions are summarized in Fig.1 a-f. Note that by the very nature of the cubic snowflake expansion [5-7] only two nulls are present in the divertor area so that it can be called a “two-null expansion.” This expansion has also been extensively used in Ref. 1.

An exact snowflake would correspond to a second-order null, but if the nulls are sufficiently close to each other (see below for more detail), the resulting configurations will still behave as a snowflake. In this regard, any of the two-null configurations shown in Fig. 1 a-e are indeed snowflakes, provided the distance between the nulls is sufficiently small. What "sufficiently small" means depends of the specifics of the problem under consideration. In particular, if one is interested in the effect on the SOL, the distance d_{xpt} between the nulls has to be less than the thickness of the SOL in the vicinity of the null. As shown in Refs. 5, 6, this criterion can be expressed as

$$d_{xpt} < Ca(\Delta/a)^{1/3}, \tag{1}$$

where Δ is a midplane SOL width, a is the minor radius and C is a numerical coefficient of order unity. This "proximity condition" for the other phenomena affected by the two nearby nulls (e.g., the prompt ion loss) is discussed in Ref. 9.

To compare the snowflake divertor with the X-divertor of Refs. [5-7], we present a schematic of the X-divertor in Fig. g (in Ref.1 there are no figures from the original X-divertor papers [2-4]). The approach of Refs. [2-4] is clear and compelling: it includes the dipole poloidal field (PF) coils situated very near the divertor targets that generate a magnetic field opposite to the field of the standard divertor, thereby leading to a significant flux expansion on the targets. [By the "dipole" we mean, following the authors of [2-4], two equal axisymmetric currents flowing in the opposite directions.] Note that a conceptually similar configuration was described in Ref. 11. In Refs. 2-4, an elegant idea of replacing the dipole coils by the closed current loops that could be inserted in the gaps between the toroidal field coils and thereby bringing the currents close to the divertor target is also described (Fig. 1 in Ref. 2, Fig. 5 of Ref. 3, and Fig. 3a of Ref. 4).

One can immediately see that none of the near-SF configurations of Fig. 1a-f has much in common with the configuration of Fig. 1g. This is because the magnetic field in the "snowflake expansion" of Refs. 5-7 is smooth and varies on the scale significantly larger than the distance between the nulls, whereas for the arrangement of Fig.1g, the opposite is true. In particular, each set of the dipole coils creates not one, but two nulls (Fig. 1g), and it is misleading to describe this configuration as an X-point (as the authors of Ref. 1 do): the second null is quite close to the first one (in each dipole) and the field structure on the target is affected by both of them.

In the original X-divertor papers [2-4] the authors have considered the arrangement of Fig. 1g with the flux flaring in both divertor legs. This is indeed quite important since the energy deposition during the ELM events oftentimes reveals a larger fraction of the ELM energy dumped in the inner divertor [9]. In Ref. 1, the authors, instead of the original approach of Ref. 2-4, switch to the configurations based on the SF two-null expansions of Ref. 7. This means that only one divertor leg can be taken care of (in Ref. 1 this is the outer leg), with the inner leg left without flux flaring. Note that in the snowflake approach, strong flux expansion occurs both in the inner and outer SOL and, in addition, the power can be shared between four divertor legs.

The authors of Ref. 1 indicate that the flux flaring in one divertor leg is possible with the original arrangement of Fig. 1g. This is true, one can do that by using the dipole coils in the outer leg only. Still, the difference between the snowflake and X-divertor remains quite dramatic. This difference is hard to see from the figures presented in Ref. 1, in particular, from Fig. 6a, where the information of the complete structure of the field in NSTX divertor, e.g., [12, 13], is completely obscured by because only one flux surface (aside from the separatrix) is shown. The real field in NSTX divertor (Fig. 2) has no resemblance to the structure produced by the prescription of Refs. 2-4, Fig.1g. A sketch of the original, 2004-2007 outer leg of the X-divertor is shown in Fig. 6b of Ref. 1

without nearby coils and does not allow the reader to appreciate the structure and spatial scales of the magnetic field variation. This omission makes a meaningful comparison with the actual NSTX configuration impossible.

The realization that the magnetic field structure in the divertor can be controlled by remote coils was an important ingredient of the snowflake development, which was entirely missing from the prescriptions of the 2004-2007 X-divertor publications which, again, all had coils in close proximity to the target plates. The versions of what is called now an X-divertor in Ref. 1 are based on the snowflake expansions of Refs. [6, 7].

In Sec. IIID of Ref. 1, the authors correctly indicate that a particular magnetic field structure in a certain region can be generated by a variety of current distributions flowing outside this region. The currents can flow, in particular, very near the boundary of this region. For example, the currents could flow just behind the walls of the vacuum vessel. The authors refer to this fact to indicate that the fields created by remote coils outside the vacuum vessel (and therefore smooth in the divertor region) are irrelevant for their analysis. Indeed, if one wants to generate exactly the same fields as those created by the remote coils, one can do that by currents flowing as close to the vacuum wall as one wants. However, for these currents to create the same field inside the vessel, one would have to solve a boundary-value problem that intrinsically couples to the field in the external space. Accordingly, the required current distribution "knows" of the field outside, so that this field is highly relevant, even though it is situated outside the vessel. To generate, e.g., a smooth SF-minus configuration this near-wall current distribution will have to be drastically different from the two-conductor dipoles of Fig. 1g. In addition, the knowledge of the magnetic field at larger distances from the divertor is needed to properly orient the coordinate frame and the field structures of Fig. 1 a-f (see Fig.3 in Ref. 7).

Our next concern is related to the concept of a "divertor index" (*DI*) introduced in Ref. 1. The index is supposed to characterize the flux expansion (contraction) along the flux surface between the point nearest to the main null and the strike point. Perhaps, a more relevant measure could be simply the flux expansion between the midplane SOL and the strike point. An exact snowflake certainly creates significantly stronger midplane-to-target flux expansion than the standard divertor for the targets placed at the same distance from the PF null. The divertor index does not account for this simple but important feature.

Application of the divertor index to the two-null configurations stemming from the snowflake expansions of Ref. 6, 7 is even more confusing. Figure 2 shows the divertor index evaluated according to Eq. (4) of Ref. 1 for an actual NSTX tokamak geometry. One sees that the *DI* varies from values less than one to values greater than one along the divertor floor, making the use of the *DI* for characterization of the magnetic configurations quite problematic. It would be helpful if the authors produced the plot of the divertor index vs. position on the target plate for the original X-divertor configuration of Fig. 1g.

To mitigate this uncertainty, one could average the *DI* over the target, but to do that in a meaningful way one needs to have information about the heat-flux distribution which should be used as a weighing function. Also, the fact that in real two-null geometries some of the flux surfaces are diverging towards the target, whereas others are converging, makes an assessment of the effect of convergence/divergence on the plasma detachment (Sec. IV of Ref.1) inconclusive.

We fully agree with the authors of Ref. 1 that the position and shape of the divertor plates is very important for divertor performance. For the case of a snowflake, these effects have, in particular, been studied in Refs. 14, 15. The full optimization of the snowflake divertors is still a matter for the future work, but it is hard to see how application of the divertor index could help in guiding this optimization.

In conjunction with the issue of the flux expansion, the authors state (Sec. 3C, above Fig. 9): "Since spreading heat at the divertor plate is one major mission of the advanced divertor enterprise and it is the XD configuration that affects the largest flux expansion at the plate, the XD route is strongly indicated as the best divertor choice." On the other hand, the usable poloidal flux expansion at the plate may be limited by a variety of practical considerations, as the authors of the X-divertor concept correctly indicate in Ref. 16 (see discussion preceding Eq. (1) in Ref. 16). And, again, characterization of the divertor "quality" only by the flux expansion in the outer SOL completely misses the possibility of splitting the flux between multiple strike points, as is the case with a snowflake [10, 17-19].

One of the configurations covered by the two-null SF expansion of Ref. 7, the configuration of a symmetric snowflake-minus shown in Figs. 1a, and 1d, is notable in that both nulls lie on the same flux-surface. When the nulls are close to each other, so that condition (1) is satisfied, it represents a snowflake (with regard to SOL processes). If the distance becomes larger than (1), and the configuration loses SF features, it can still be described by the two-null expansion, provided the PF coils are sufficiently far away and the cubic expansion still holds. When this configuration is oriented as in Fig. 1 d, it produces strong flux expansion near the strike point of one of the branches of the separatrix, Fig. 3. The configuration is not a snowflake (if condition (1) is violated), but it is also not an X-divertor of the type shown in Fig. 1g. We suggest naming it the "trident configuration," shown in Fig. 3, because there are three outgoing branches of the separatrix emerging from the outer null. Note that because the trident configuration can be described by the cubic expansion, there are only two nulls, and the inner divertor leg remains unaffected as it would be in the X-divertor of Fig. 1g or in a snowflake divertor, with its high flux expansion and the possibility for splitting the flux between multiple strike points.

One of the major points made in Ref. 1 is an assertion (repeated in various forms many times throughout the paper) that "recent National Spherical Torus Experiment and DIIID experiments are X-Divertors, not Snowflakes." However, the XD concept known at the time these experiments were conceived (see, e.g., Ref. 20) and performed (e.g., Refs. 12, 13, 21, 22), implied a specific engineering approach – using additional coils near the target plates. Neither NSTX nor DIII-D experiments did use additional coils but rather used manipulation of existing PF coils, which was a major ingredient of the SF approach. These experiments showed effects on the target plate that may be attributable to poloidal flux expansion on the plate, but poloidal flux expansion was a part of our vision of the SF divertor, and our published analyses of the SF, including UEDGE plasma transport simulations, were explicit about this. Also, most important for qualifying as an SF configuration, the "proximity constraint" (1) was satisfied in both NSTX and DIII-D experiments, and the magnetic field structure in the divertors matched very well the snowflake expansion of Refs. 5-7. So, the previous identification of the configurations realized in these experiments as a snowflake is correct.

In conclusion:

a) The capability of a tokamak divertor to handle heat and particle fluxes is determined by processes that encompass the pedestal, the private flux region and all the divertor legs and cannot be reduced to the magnetic field structure in the outer SOL.

b) The concept of the divertor index as defined in Ref. 1 focuses on only one feature of the magnetic field structure and can be quite misleading when applied to guide divertor design.

c) The Ref. 1 suggestion to rename the divertor configurations experimentally realized on NSTX and DIII-D experiments from snowflakes to X-divertors is not warranted (i) because the comparison of the NSTX and DIII-D divertors with the prototypical X-divertor as described in Fig.1g reveals completely different geometry (Fig. 2a) and, (ii) because the NSTX and DIII-D field geometries satisfy the proximity condition between the magnetic nulls and SOL as defined in Equation (1) and References [5, 6, 10].

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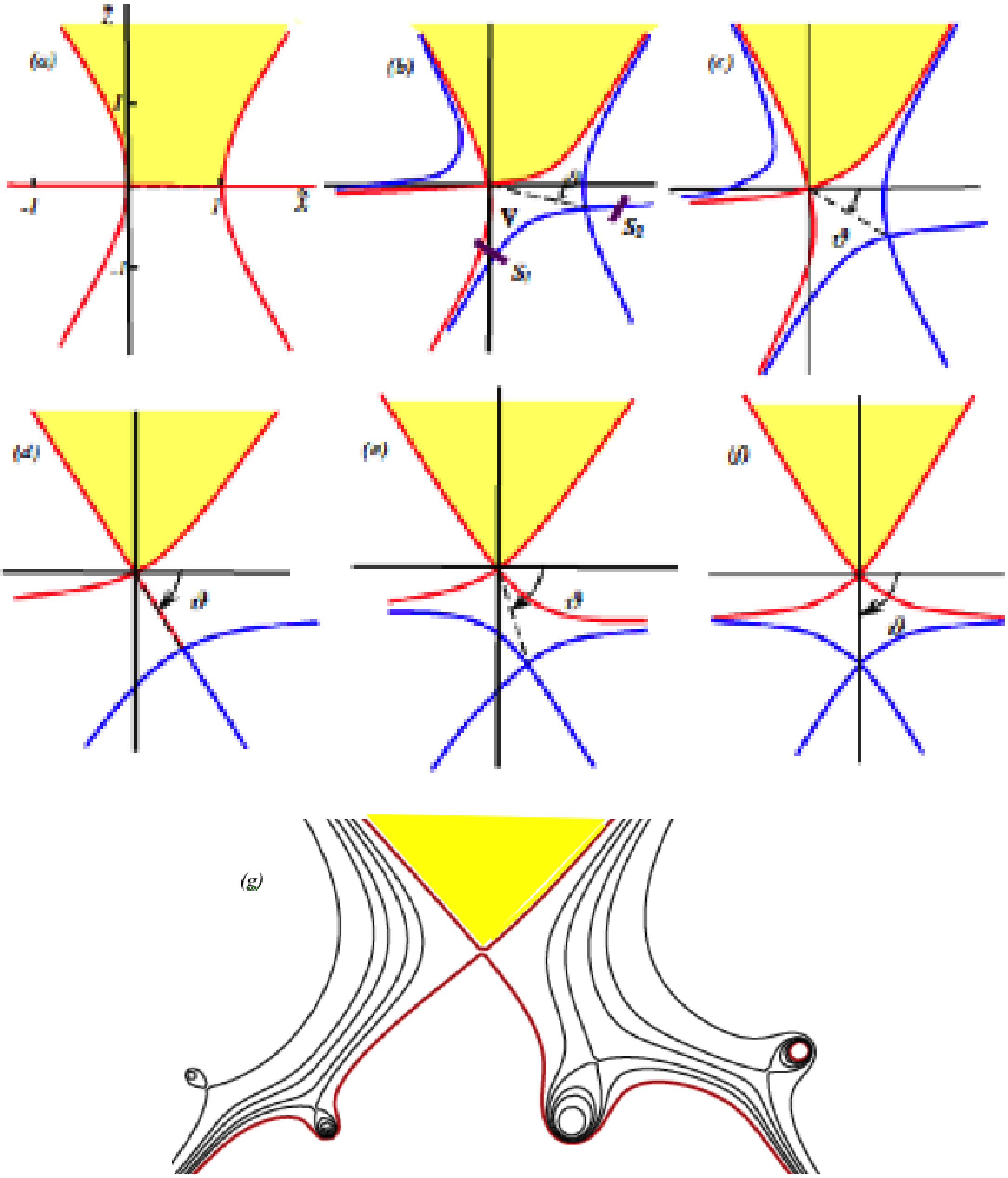

Fig. 1 A family of the snowflake configurations (a)-(f) [4] created by remote coils and. (g) a sketch of a possible X-divertor configuration based on approach of Refs. 5-7.. The difference of the field structures between (g) and any of the (a) – (f) is dramatic.

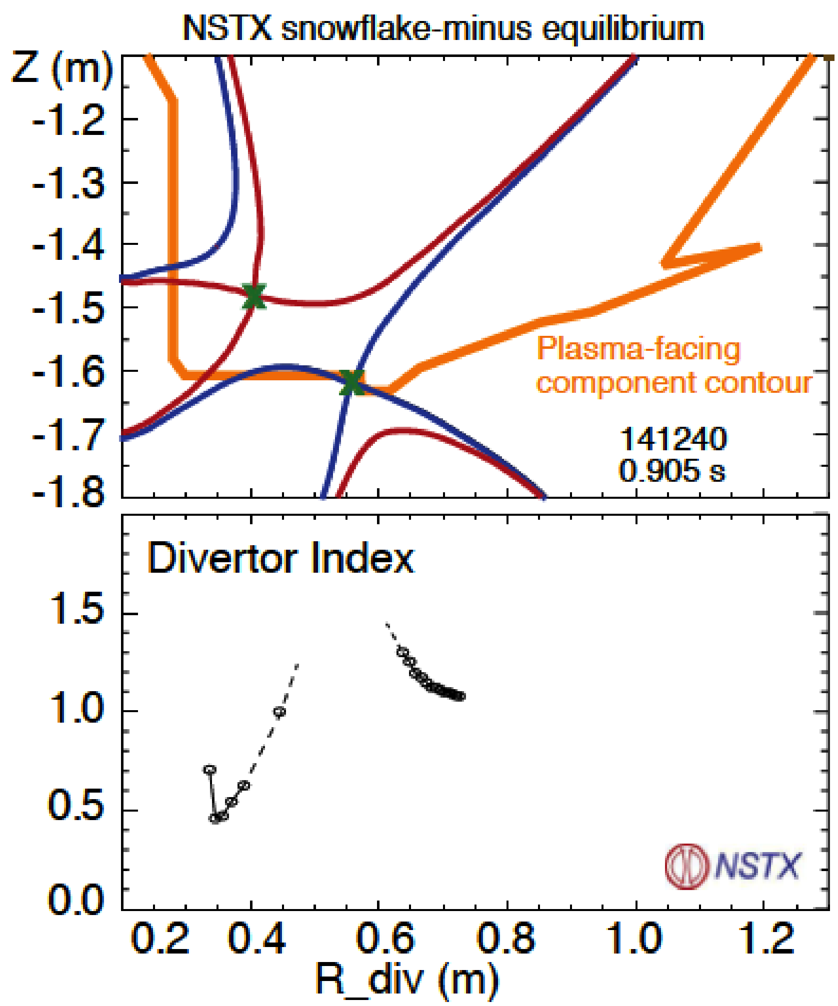

Fig. 2 NSTX SF-minus magnetic field configuration (upper panel), and the divertor index (lower panel). The shape of the flux surfaces in the divertor area almost perfectly fits the two-null expansion. According to the prescriptions made in Ref. 1, part of the divertor is a snowflake-like (DI<1), whereas the other part is a standard or X-divertor (DI>1.

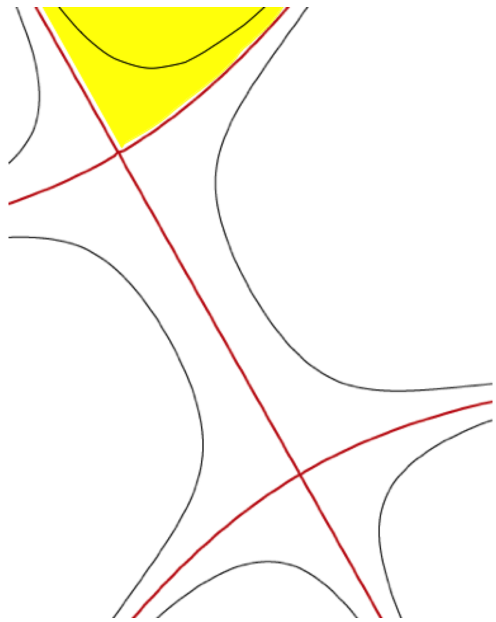

Fig. 3 A trident divertor configuration. The confinement zone is shown in yellow as in Fig 1d. This configuration is generated by the same expansion as Fig. 1d, just with a larger distance between the nulls.